



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Light induced waveguides in nematic liquid crystals

Citation for published version:

Assanto, G & Smyth, N 2016, 'Light induced waveguides in nematic liquid crystals', *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 22, no. 2, 4400306.
<https://doi.org/10.1109/JSTQE.2015.2446762>

Digital Object Identifier (DOI):

[10.1109/JSTQE.2015.2446762](https://doi.org/10.1109/JSTQE.2015.2446762)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

IEEE Journal of Selected Topics in Quantum Electronics

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Light Induced Waveguides in Nematic Liquid Crystals

Gaetano Assanto, *Fellow IEEE* and Noel F. Smyth

Abstract—Spatial optical solitary waves in media with nonlinear refractive index are self-localized beams as well as waveguides induced by light. We review their guiding features in reorientational birefringent soft matter, namely nematic liquid crystals, for which a highly “nonlocal” response enhances the confinement, stabilization and robustness of the generated optical solitary waves, termed “nematicons.” The waveguiding properties of spatial solitons in nematic liquid crystals are illustrated through the confinement of low power signals and other solitary waves, as well as optical vortices.

Index Terms—Solitons, Liquid crystals, Nonlinear optics, Optical solitons, Optical vortices

I. INTRODUCTION

Nematic liquid crystals can be considered an ideal medium for exploring nonlinear optical effects and light manipulation [1], [2]. This is due to their “huge” nonlinearity and negligible absorption, so that nonlinear optical effects occur at power levels of the order of milliwatts and over millimeter distances. Nematic liquid crystals (NLC) belong to a broad class of materials termed soft matter, in that they form an elastic medium which can flow while maintaining a finite order, hence their name [3]. In standard forms, they consist of elongated organic molecules which, in the nematic phase, possess a large degree of orientational order, but negligible positional order. NLC molecules contain benzene rings, so that their electrons exhibit a high non-localization and can easily move in the presence of an electric field, giving rise to dipoles which are able to rotate, opposing the intermolecular links (elastic forces) in order to align to the field vector and so reduce the interaction energy. Such a “reorientational” response manifests itself both as an electro-optic effect and as an all-optical nonlinearity. For the latter, since “reoriented” dipoles correspond to a “rotated” optic axis (or molecular director) in the macroscopic uniaxial dielectric, the refractive index increases in a nonlinear manner under the action of light in the extraordinary polarization, i.e. with electric field coplanar with the wavevector and optic axis [3]. Therefore, beams of light with polarized electric field non-orthogonal to the molecular director can undergo self-focusing through all-optical reorientation, eventually balancing diffraction and supporting the generation of self-confined transversely invariant spatial solitary waves, or simply solitons. The term “nematicon” refers to such self-trapped beams and

the corresponding refractive index potentials or waveguides in nematic liquid crystals [1], [2], [4].

Optical solitary waves in nematic liquid crystals, nematicons, have been proposed as the basis for all-optical circuits [4], [5], [6], with several functionalities relying on their use as reconfigurable/readressable waveguides. Here we will review some of the configurations proposed for nematicon waveguide applications. Nematicon waveguides can be controlled through external electric fields [1], [7] or by interaction with other optical beams [1], [8], [9], [10], [11], [12], [13]. Since nematicons are nonlinear optical beams, they can alter their uniaxial environment and so change their own path [14]. Furthermore, since NLC are nonlocal in that the response to an optical beam extends far beyond its waist [1], [2], [15], nematicons can act on each other at a distance through the medium [16], [17], [18]. Finally, a nematicon waveguide can stabilize beams which tend to become unstable upon interacting with, for example, refractive index perturbations [19], [20], [21]. In the following we shall address these features and properties of nematicon waveguides.

II. GOVERNING EQUATIONS

Let us consider the propagation of a linearly polarized beam of light through a planar cell filled with undoped nematic liquid crystals. Let the propagation direction of the beam be z and the direction perpendicular to the confining interfaces be x , with y completing the coordinate triad. The complex valued envelope of the electric field of the beam will be denoted by u . To overcome the optical Freédricksz threshold [3] occurring when field and director are orthogonal, the nematic molecules are pre-tilted at an angle θ_0 to the propagation direction. This is achieved by either applying a low frequency electric field (bias voltage) across the cell thickness in the (x, z) plane or by “rubbing” the planar interfaces of the cell, so that the director is aligned to the rubbing direction in the (y, z) plane, with this alignment spread into the bulk via the intermolecular links. The angle θ will then denote the extra nonlinear rotation given to the molecules (director) by the light beam, so that the total angle the director makes to the z direction is $\theta_0 + \theta$. The non-dimensional equations governing the propagation of light in the paraxial, slowly varying envelope approximation are [1], [2], [15], [22], [23]

$$i \frac{\partial u}{\partial z} + \frac{1}{2} \nabla^2 u + 2\theta u = 0, \quad (1)$$

$$\nu \nabla^2 \theta - 2q\theta = -2|u|^2. \quad (2)$$

Equation (1) governs the evolution of the electric field of the light beam, with equation (2) giving the resulting NLC

G. Assanto is with **NooEL**— Nonlinear Optics and OptoElectronics Lab University of Rome “Roma Tre”, 00146 Rome, Italy and Optics Lab, Tampere University of Technology, FI-33101 Tampere, Finland email: assanto@uniroma3.it

N.F. Smyth is with School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, Scotland, U.K. email: N.Smyth@ed.ac.uk

response in terms of the reorientation angle. These equations form a coupled system. The Laplacian in these equations is in the transverse (x, y) plane. The parameter ν measures the strength of the elastic forces (nonlocality) in the NLC and is $O(100)$ in most experimental regimes [1], [24], [25]. The parameter q is proportional to the square of the pre-tilting electric field across x or related to the rest angle in the case of “rubbing” in yz [15], [26]. As inherent to the propagation of extraordinarily polarized light in uniaxials, the Poynting vector (power flow direction) for the extraordinary beam is at a “walkoff” angle to the input direction of its wavevector, around a maximum value of 7° in NLC with the usual birefringence of about 0.2 [1], [2]. The walkoff, associated with nonlinear beams as well [1], [2], has been factored out of the electric field equation (1) by a phase transformation [18], [27]. A typical cell thickness is $75\mu\text{m}$ and a typical input beam width is $4\mu\text{m}$ for visible/near infrared wavelengths [28]. As the electric field u and the director angle perturbation θ decay exponentially away from the beam profile, the effect of the cell interfaces can be neglected for beams launched along z around the middle of the cell across x . We shall therefore take the NLC sample to be infinite when deriving solutions of the nematic equations (1) and (2).

While the system of equations (1) and (2) has been derived for optical beam propagation in nematic liquid crystals, it is more general and holds for nonlinear beam propagation in media whose response is governed by some type of diffusive phenomenon [29]. For example, the system of equations (1) and (2) governs light beam propagation in thermo-optic media [30], such as lead glasses [31], [32], [33], and in photorefractive crystals [34], [35]. The same system also arises in α models of fluid turbulence [36], [37] and in the Schrödinger-Newton model of quantum gravity [38], [39].

The nematic equations (1) and (2) possess a solitary wave solution, termed a nematicon [1], [2], [4], [26]. Numerical methods can be used to find this nematicon solution [40], [41], [42], but there is no known general analytical nematicon solution, just specific ones for fixed parameter values of ν and q [43]. A nematicon is formed by a balance of the nonlinear self-focusing in the NLC with linear diffractive spreading [1], [2]. The corresponding refractive index distortion is a graded-index waveguide, able to confine other optical signals [26], with or without angular momentum. A nematicon waveguide can also stabilize, or enhance the stability of, a co-propagating optical beam.

For the numerical solutions of the nematic equations presented in this work, the electric field equation (1) and its extensions dealt with below were solved using the pseudo-spectral method of Fornberg and Whitham [44]. The elliptic director equation (2) and its extensions were solved using a Fourier method outlined in [45].

III. NEMATICON WAVEGUIDES

The waveguiding capabilities of a nematicon were detailed in the early work in which a nematicon was experimentally demonstrated by exploiting the reorientational response of undoped NLC [26]. The guidance of a longer wavelength signal

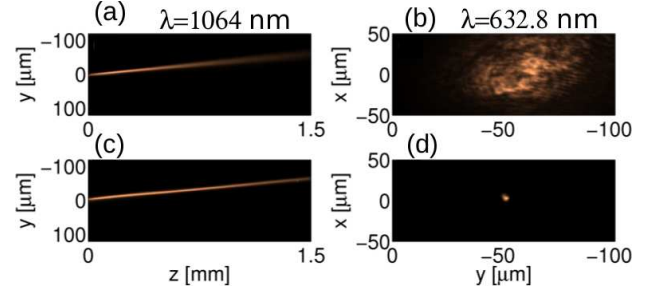


Fig. 1. (Color online) Weak probe beam of wavelength 632.8nm (Helium-Neon laser) and power $30\mu\text{W}$ col launched and copolarized with a nonlinear beam of wavelength 1064nm (Nd-YAG laser) in a planar cell with optic axis aligned at 45° with respect to z in the plane (y, z) . (a) Linear propagation of the near-infrared beam of (low) power 0.5mW in the plane (y, z) . The beam diffracts and walks off. (b) Transverse profile, (x, y) , of the probe at the cell output. (c) Evolution in (y, z) of a nematicon generated by a 2mW near infrared beam. (d) Corresponding output profile of the weak probe guided by the nematicon waveguide.

(632.8nm) by a fundamental order solitary wave launched at 514nm was supported by the large numerical aperture associated with the nonlocal response of the NLC [26], a property responsible for the formation of nematicons, even with spatially incoherent light [24], [43], [46]. The formation of a nematicon waveguide from a 1064nm Nd:YAG laser of power 2.0mW and the confinement of a co-propagating weak, $30\mu\text{W}$ copolarized probe from a Helium-Neon laser of wavelength 632.8nm is illustrated by photographs in Figure 1 for the case of a cell with optic axis planarly aligned at 45° with respect to z . Figure 1(a) shows the evolution of a low power (i.e. linear) beam which diffracts, since it does not carry enough power to form a nematicon, and propagates with walkoff (about 7°) with respect to its wavevector along z . A red low power probe beam, col launched and copolarized (with input electric field oscillating along y), also diffracts and spreads in the transverse (x, y) plane, as seen in Figure 1(b) after propagating over 1mm . For an input nonlinear beam of sufficient power, a diffractionless nematicon is formed, as in Figure 1(c). This nematicon is also a waveguide for the weak probe, which gets confined, as shown in Figure 1(d). The red light does not diffract and remains confined and bell shaped in (x, y) at the cell output.

This guiding of a low power signal by a nematicon was extended in a recent numerical and theoretical study of the interaction between two such beams [47]. This study included a detailed investigation of how the trajectory of the nematicon could be controlled by the low power beam, with trajectory deviation resulting from momentum exchange between the beams.

Reorientational nematic liquid crystals are a self-focusing medium, so that regions of higher beam intensity tend to exhibit higher refractive index. However, a light-induced reduction in the order parameter through the introduction of dopants, such as azo-dyes, can turn the NLC into a self-defocusing medium, so that dark solitary waves can be excited [48]. For a defocusing NLC, the electric field equation (1) becomes

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial x^2} - 2\theta u = 0 \quad (3)$$

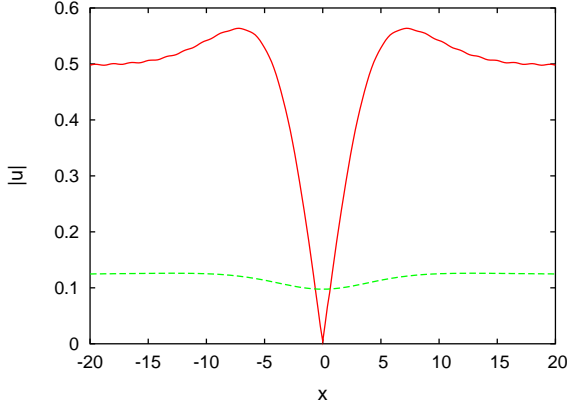


Fig. 2. (Color online) Dark nematicon solution of the dark nematicon equations (3) and (2). Electric field $|u|$: red (solid) line, director θ : green (dashed) line. Parameter values are $u_0 = 0.5$, $\nu = 200$ and $q = 2$.

for one-dimensional dark solitons [49]. The self-defocusing nematic equations (2) and (3) support dark nematicons, solitary waves which are dips in a background carrier wave, rather than the intensity hump of the “bright” nematicons of the focusing equations (1) and (2).

Dark nematicon solutions on a constant background are of the form

$$u = f(x - Uz)e^{-2iu_0^2 z/q}, \quad (4)$$

for a (complex) function f which gives the dark nematicon profile [50]. A typical dark nematicon solution is shown in Figure 2 and differs from the dark soliton solution of the nonlinear Schrödinger equation [49]. This can be seen in Figure 2 as two humps in the electric field at the tails of the dark nematicon. These humps are due to a linear wave mode trapped in the tail of the dark nematicon owing to the nonlocal response of the NLC [50] which extends well beyond the beam. A mathematical dark nematicon (4) differs from an experimental dark nematicon: the former has a carrier wave which extends to $x = \pm\infty$, whereas in the latter the carrier wave has a finite extent, often Gaussian. Nevertheless, in both limits dark nematicons are associated with a coaxial graded-index waveguide supporting the guided co-propagation of a (bright) linear signal. This property was exploited to experimentally guide a longer wavelength copolarized probe in a dark nematicon [48].

Figure 3 shows simulated and experimental results obtained in an azo-doped NLC cell with resonant absorption around 475nm . In Figure 3(a) the simulated diffraction of a linear (bell shaped) beam with a central dip (top) is compared with the simulated evolution of a dark nematicon (bottom). As expected, the low power beam diffracts (the notch gets wider), whereas the high power nematicon remains self-confined. The corresponding experimental results for extraordinary polarized light in Figure 3(b) show a low power (0.1mW) dark beam at 532nm diffracting along z (top), whereas at high power (4mW) it gives rise to a self-confined dark nematicon. The propagation of a weak (0.1mW) copolarized bell-shaped probe at 1064nm is illustrated in Figure 3(c). When collaunched in the low power dark beam, the probe diffracts as expected (top), whereas when the dark nematicon is formed,

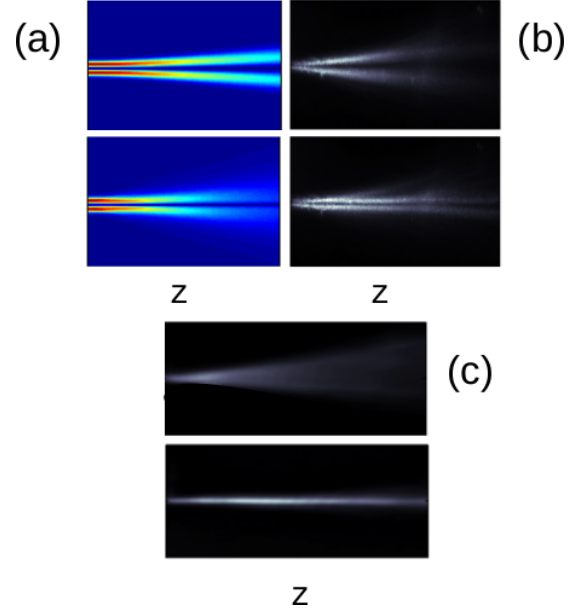


Fig. 3. (Color online) Simulation and experimental results for a dark nematicon on a finite Gaussian background. (a) Simulation of a linear, bell-shaped beam with a central notch (top), simulation of a dark nematicon (bottom). (b) Experimental results for a lower power, 0.1mW , dark beam (top), dark nematicon formed at high power, 4mW (bottom), both at 532nm . (c) Evolution of a copolarized, weak 0.1mW , bright bell-shaped probe at 1064nm collaunched with either the low power 532nm dark beam (top) or the 532nm dark nematicon (bottom).

the near-infrared signal is trapped by the dark nematicon waveguide (bottom) [48].

IV. MUTUALLY GUIDING NEMATICONS

Being nonlinear waveguides, nematicons can produce confining effects not only on weaker probes, but also on other nonlinear beams and nematicons. Let us first consider the incoherent interaction of two nematicons of different wavelengths (colors), as discussed in [18], [17]. The extension of the (non-dimensional) nematic equations (1) and (2) to this two color case is [51]

$$i\frac{\partial u}{\partial z} + \frac{1}{2}D_u\nabla^2 u + 2A_u\theta u = 0, \quad (5)$$

$$i\frac{\partial v}{\partial z} + \frac{1}{2}D_v\nabla^2 v + 2A_v\theta v = 0, \quad (6)$$

$$\nu\nabla^2\theta - 2q\theta = -2A_u|u|^2 - 2A_v|v|^2. \quad (7)$$

Here u and v are the complex valued envelopes of the electric fields of the two beams. As the two beams have different wavelengths, they have different diffraction coefficients D_u and D_v , and interaction strengths A_u and A_v with the NLC. For instance, for the experiments of Alberucci *et al* [51] the diffraction coefficients were 0.805 for red and 0.823 for near-infrared light, respectively. The initial beams in the modes u and v can be taken to be

$$u = a_u \text{sech} \frac{\chi_u}{w_u} e^{i\psi_u}, \quad v = a_v \text{sech} \frac{\chi_v}{w_v} e^{i\psi_v}, \quad (8)$$

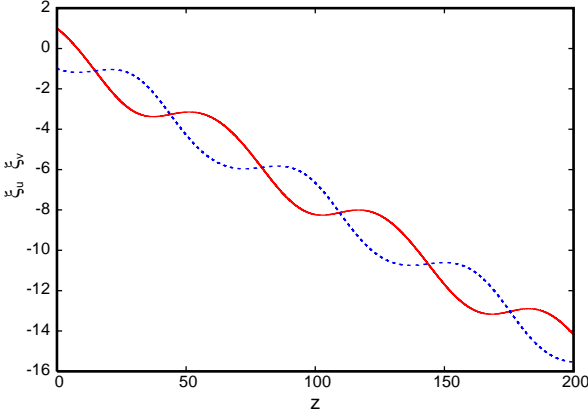


Fig. 4. Coupled nematicon positions for the initial values $a_u = a_v = 1.8$, $w_u = w_v = 3.0$, $\xi_u = 1.0$, $\xi_v = -1.0$, $U_u = 0.1$, $U_v = -0.05$, $V_u = V_v = 0.0$ with $\nu = 500$, $q = 2$, $A_u = 1.0$, $A_v = 0.95$, $D_u = 1.0$, $D_v = 0.98$. u mode: red (solid) line, v mode: blue (dotted) line.

where

$$\begin{aligned}\chi_u &= \sqrt{(x - \xi_u)^2 + (y - \eta_u)^2}, \\ \chi_v &= \sqrt{(x - \xi_v)^2 + (y - \eta_v)^2} \\ \psi_u &= U_u(x - \xi_u) + V_u(y - \eta_u), \\ \psi_v &= U_v(x - \xi_v) + V_v(y - \eta_v).\end{aligned}\quad (9)$$

In the u mode these represent a beam of amplitude a_u and width w_u centered at $(\xi_u, 0)$ propagating at initial angles $\tan^{-1} U_u$ and $\tan^{-1} V_u$ to the z direction in the (x, z) and (y, z) planes, respectively, and similarly for the v component.

The guiding of a nematicon by another nematicon of different wavelength is illustrated in Fig. 4, which gives the trajectory of the peaks (amplitude) of the nematicons in the u and v wavelengths. It is important to recall that NLC is a highly nonlocal medium, so that the response of the nematic to the optical beam extends far beyond the beam waist [1], [2], [15]. This further implies that, even though the beams are not overlapping, the waveguiding effect (index potential) of a given beam can extend to the other one, resulting in mutual attraction and oscillation about one another [16]. It can be seen from Figure 4 that the mean position of the interacting nematicons follows a downward path. This is due to overall momentum conservation as the total beam momentum

$$P = a_u^2 w_u^2 U_u + a_v^2 w_v^2 U_v \quad (10)$$

is conserved [18], with the individual nematicon trajectories given by [18]

$$\frac{d\xi_u}{dz} = D_u U_u, \quad \frac{d\xi_v}{dz} = D_v U_v. \quad (11)$$

As the initial “velocities” U_u and U_v for the trajectories in Figure 4 are not equal and opposite, the mean trajectory of the nematicon pair has a non-zero transverse “velocity”. In addition, the unequal diffraction coefficients D_u and D_v contribute to produce different trajectories. As the two solitary waves oscillate about each other, they shed diffractive radiation, which takes away momentum from the nematicons and so reduces the amplitude of their oscillations about each

other until they share the same trajectory [18]. Due to the large nonlocality ν , this occurs over a very long z distance as the loss to radiation scales as $1/\sqrt{\nu}$ [52].

V. NEMATICONS GUIDING OPTICAL VORTICES

Let us now consider the guidance of an optical vortex by a co-propagating nematicon, as studied in [19], [20], [21]. As expected on the basis of the highly nonlocal medium response, the nematicon acts as a waveguide even for a vortex: while an isolated vortex could not survive interaction with an index perturbation or interface and undergo stable refraction, in the presence of a coaxial nematicon it gets stabilized by the nonlinear index potential and can be deviated/refracted [19], [20], [21]. We consider a nematicon and a vortex to be generated from polarized beams of the same wavelength, so that we can take $D_u = D_v = 1$ and $A_u = A_v = 1$ in terms of the two color nematic equations (5)–(7). The NLC can have an imposed refractive index potential generated, for instance, by voltages applied across its thickness [11], [12], [13], by finite light beams travelling through the cell [8], [9], [10] or nonuniform anchoring. If this index potential has the general form $\mathcal{F}(x, z)$, the non-dimensional equations governing the guiding of the optical vortex by the nematicon are [2], [51], [53]

$$i \frac{\partial u}{\partial z} + \frac{1}{2} \nabla^2 u + 2\mathcal{F}(x, z)u + 2\theta u = 0, \quad (12)$$

$$i \frac{\partial v}{\partial z} + \frac{1}{2} \nabla^2 v + 2\mathcal{F}(x, z)v + 2\theta v = 0, \quad (13)$$

$$\nu \nabla^2 \theta - 2q\theta = -2|u|^2 - 2|v|^2. \quad (14)$$

The initial beams are taken to be

$$u = a_u \operatorname{sech} \frac{\sqrt{(x - \xi_u)^2 + y^2}}{w_u} e^{i\sigma_u + iU_u(x - \xi_u)} \quad (15)$$

$$v = a_v r e^{-r/w_v} e^{i\sigma_v + iU_v(x - \xi_v) + i\phi}. \quad (16)$$

The coordinates (r, ϕ) are plane polar coordinates centered at the initial position of the vortex $(\xi_v, 0)$. For simplicity we assume a Gaussian refractive index variation

$$\mathcal{F}(x, z) = A_D e^{-(x - X)^2 + (z - Z)^2} / W^2. \quad (17)$$

centered at (X, Z) [54], [55]. The initial beam (15) is again a beam of amplitude a_u and width w_u centered at $(\xi_u, 0)$ and propagating at an initial angle $\tan^{-1} U_u$ to the z direction in the (x, z) plane. The beam (16) is a vortex of amplitude $a_v w_v e^{-1}$ and width w_v centered at $(\xi_v, 0)$ and propagating at an angle $\tan^{-1} U_v$ to the z direction in the (x, z) plane.

The stable confinement of an optical vortex in the nematicon waveguide is illustrated in Figure 5. The white curves in this figure mark the curve along which the refractive index change \mathcal{F} given by (17) is half its peak value. Fig. 5(a) shows that, in the absence of the guiding nematicon and the refractive index change (17), the vortex is stable, with Fig. 5(b) showing that the refractive index change destabilizes the vortex. The vortex is actually pulled apart by its different portions being subjected to different local refractive indices. Propagating the optical vortex through a nematicon waveguide has a major effect on its stability under refraction, as visible in Figs. 5(c) and (d).

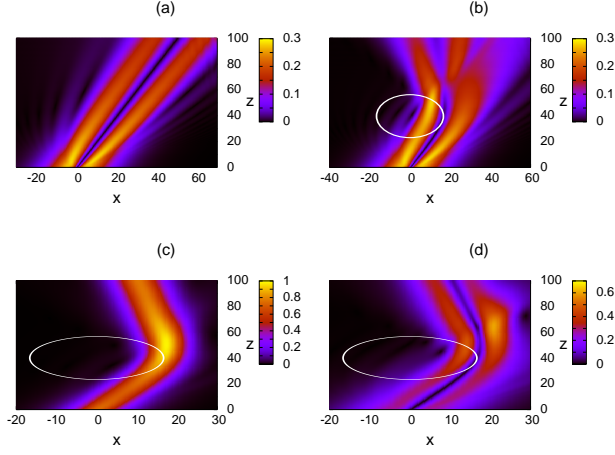


Fig. 5. (Color online) Evolution of nematicon and vortex for $a_v = 0.15$, $w_u = 4.0$, $w_v = 5.0$, $U_u = U_v = 0.5$, $\xi_u = \xi_v = 0$ at $z = 0$ with $q = 2$, $\nu = 200$, $(X, Z) = (0, 40)$ and $W = 20$. (a) vortex $|v|$ for $a_u = 0$, $A_D = 0$, (b) vortex $|v|$ for $a_u = 0$, $A_D = 0.25$, (c) nematicon $|u|$ for $a_u = 0.75$, $A_D = 0.25$, (d) vortex $|v|$ for $a_u = 0.75$, $A_D = 0.25$.

Figure 5(c) shows that the nematicon is a stable waveguide on refraction by the localized refractive index change. Fig. 5(d) then shows that guiding by the nematicon also results in the stable refraction of the vortex, in contrast to the instability seen in Fig. 5(b) without the nematicon. The vortex undergoes some distortion on refraction, but is not pulled apart as in Fig. 5(b).

The stable routing of an optical vortex by a nematicon around a localized index change can be extended to the classical optics problem of a beam refracted at a linear interface between two regions of different refractive indices [21]. To eliminate numerical instabilities, the linear interface between the regions of different refractive indices in the (x, z) plane was smoothed as

$$\mathcal{F}(x, z) = \frac{A_D}{2} \left[1 - \tanh \frac{x - \mu_0 z - \mu_1}{W} \right]. \quad (18)$$

Figure 6 illustrates the refraction of a guided vortex, as governed by the nematic equations (12)–(14). Figs. 6(a) and (b) show the stable refraction of a vortex confined by the nematicon. The white line gives the location of the refractive index interface. Fig. 6(d) illustrates the stability of the vortex under refraction after it has passed through the interface. The guiding nematicon is also stable on refraction, as shown in Figure 6(c).

VI. CONCLUSIONS

Nematic liquid crystals are a highly nonlinear, nonlocal and uniaxial medium in which reconfigurable waveguides in the form of optical solitary waves, nematicons, can be formed and manipulated. Such nematicon waveguides can be used to guide low power optical signals and beams in a manner similar to other forms of optical waveguides. There are, however, a number of advantages of nematicons as optical waveguides. Nematicon trajectories can be changed by the presence of other optical beams or by the application of voltages across the sample. Therefore, these light induced guides can be

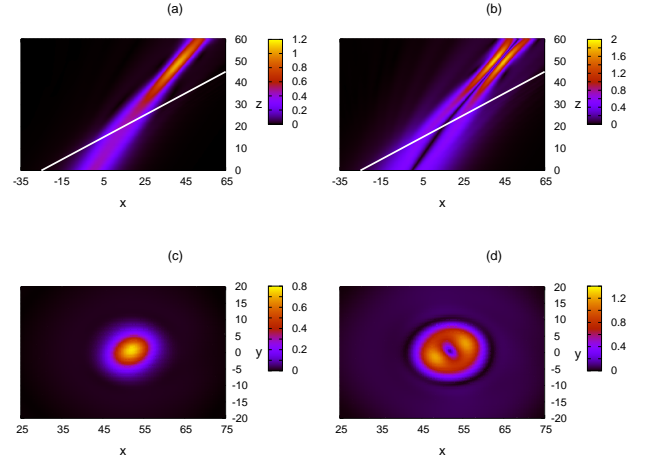


Fig. 6. (Color online) Refraction of a nematicon and a vortex for the initial values $a_u = 0.45$, $a_v = 0.25$, $w_u = 5.0$, $w_v = 5.5$, $U_u = U_v = 0.75$, $\xi_u = \xi_v = 0$, $A_D = -0.1$, $\nu = 200$, $q = 2$, $\mu_0 = 2.0$, $\mu_1 = -25.0$ and $W = 2.0$. (a) evolution of nematicon $|u|$ in (x, z) plane, white line: interface, (b) evolution of vortex $|v|$ in (x, z) plane, white line: interface, (c) nematicon $|u|$ at $z = 60$, (d) vortex $|v|$ at $z = 60$.

“redirected” and so form readdressable “circuits” to guide other signals. Nematicons can also form waveguides for high power, nonlinear optical beams, such as other nematicons. They have the further advantage of stabilizing beams, such as vortices, which can otherwise become unstable when their trajectory is changed by, for instance, regions of varying refractive index. Furthermore, since nematicons are nonlinear optical beams, the nonlinear interaction between a nematicon and another beam can be used to change the trajectories of either, or both, so that the waveguide layout becomes power dependent, with potential applications to signal control and routing. Such beam-on-beam control can be achieved in a number of different ways, with fine all-optical control by adjusting beam width and power.

VII. ACKNOWLEDGEMENTS

GA thanks the Academy of Finland for financial support through the FiDiPro grant no. 282858.

REFERENCES

- [1] M. Peccianti and G. Assanto, “Nematicons,” *Phys. Rep.* **516**, 147–208 (2012).
- [2] G. Assanto, *Nematicons, spatial optical solitons in nematic liquid crystals*, John Wiley and Sons, New York (2012).
- [3] I.C. Khoo, *Liquid Crystals: Physical Properties and Nonlinear Optical Phenomena*, Wiley, New York (1995).
- [4] G. Assanto, M. Peccianti and C. Conti, “Nematicons: optical spatial solitons in nematic liquid crystal,” *Opt. Photon. News* **14**, 44–48 (2003).
- [5] G. Assanto, A. Fratalocchi and M. Peccianti, “Spatial solitons in nematic liquid crystals: from bulk to discrete,” *Opt. Express* **15**, 5248–5259 (2007).
- [6] I.C. Khoo, “Nonlinear optics of liquid crystalline materials,” *Phys. Rep.* **471**, 221–267 (2009).
- [7] M. Peccianti, A. Dyadyusha, M. Kaczmarek, and G. Assanto, “Escaping solitons from a trapping potential,” *Phys. Rev. Lett.* **101**, 153902 (2008).
- [8] A. Pasquazi, A. Alberucci, M. Peccianti and G. Assanto, “Signal processing by opto-optical interactions between self-localized and free propagating beams in liquid crystals,” *Appl. Phys. Lett.*, **87**, 261104 (2005).

- [9] S.V. Serak, N.V. Tabiryan, M. Peccianti and G. Assanto, "Spatial soliton all-optical logic gates," *IEEE Photon. Techn. Lett.* **18**, 1287–1289 (2006).
- [10] A. Piccardi, G. Assanto, L. Lucchetti and F. Simoni, "All-optical steering of soliton waveguides in dye-doped liquid crystals," *Appl. Phys. Lett.* **93**, 171104 (2008).
- [11] A. Piccardi, A. Alberucci, U. Bortolozzo, S. Residori and G. Assanto, "Readdressable interconnects with spatial soliton waveguides in liquid crystal light valves," *IEEE Photon. Techn. Lett.* **22**, 694–696 (2010).
- [12] A. Alberucci, A. Piccardi, U. Bortolozzo, S. Residori and G. Assanto, "Nematicon all-optical control in liquid crystal light valves," *Opt. Lett.* **35**, 390–392 (2010).
- [13] A. Piccardi, A. Alberucci, U. Bortolozzo, S. Residori and G. Assanto, "Soliton gating and switching in liquid crystal light valve," *Appl. Phys. Lett.* **96**, 071104 (2010).
- [14] A. Piccardi, A. Alberucci and G. Assanto, "Soliton self-deflection via power-dependent walk-off," *Appl. Phys. Lett.*, **96**, 061105 (2010).
- [15] C. Conti, M. Peccianti and G. Assanto, "Route to nonlocality and observation of accessible solitons," *Phys. Rev. Lett.* **91**, 073901 (2003).
- [16] A. Fratalocchi, A. Piccardi, M. Peccianti and G. Assanto, "Nonlinear management of the angular momentum of soliton clusters: theory and experiments," *Phys. Rev. A* **75**, 063835 (2007).
- [17] G. Assanto, N.F. Smyth and A.L. Worthy, "Two colour, nonlocal vector solitary waves with angular momentum in nematic liquid crystals," *Phys. Rev. A* **78**, 013832 (2008).
- [18] B.D. Skuse and N.F. Smyth, "Interaction of two colour solitary waves in a liquid crystal in the nonlocal regime," *Phys. Rev. A* **79**, 063806 (2009).
- [19] G. Assanto, A.A. Minzoni and N.F. Smyth, "Vortex confinement and bending with nonlocal solitons," *Opt. Lett.* **39**, 509–512 (2014).
- [20] G. Assanto, A.A. Minzoni and N.F. Smyth, "Deflection of nematicon-vortex vector solitons in liquid crystals," *Phys. Rev. A* **89**, 013827 (2014).
- [21] G. Assanto and N. F. Smyth, "Soliton aided propagation and routing of vortex beams in nonlocal media," *J. Lasers, Opt. & Photon.* **1**, 1000105: 105–114 (2014).
- [22] A. Alberucci and G. Assanto, "Modeling nematicon propagation," *Mol. Cryst. Liq. Cryst.* **572**, 2–12 (2013).
- [23] C. García-Reimbert, A.A. Minzoni, N.F. Smyth and A.L. Worthy, "Large-amplitude nematicon propagation in a liquid crystal with local response," *J. Opt. Soc. Am. B* **23**, 2551–2558 (2006).
- [24] G. Assanto and M. Peccianti, "Spatial solitons in nematic liquid crystals," *IEEE J. Quantum Electron.* **39**, 13–21 (2003).
- [25] G. Assanto, A.A. Minzoni, M. Peccianti and N.F. Smyth, "Optical solitary waves escaping a wide trapping potential in nematic liquid crystals: modulation theory," *Phys. Rev. A* **79**, 033837 (2009).
- [26] M. Peccianti, G. Assanto, A. De Luca, C. Umetsu and I.C. Khoo, "Electrically assisted self-confinement and waveguiding in planar nematic liquid crystal cells," *Appl. Phys. Lett.* **77**, 7–9 (2000).
- [27] G.B. Whitham, *Linear and Nonlinear Waves*, J. Wiley and Sons, New York (1974).
- [28] M. Peccianti, A. Fratalocchi and G. Assanto, "Transverse dynamics of nematicons," *Opt. Express* **12**, 6524–6529 (2004).
- [29] A.B. Aceves, J.V. Moloney and A.C. Newell, "Theory of light-beam propagation at nonlinear interfaces. I Equivalent-particle theory for a single interface," *Phys. Rev. A* **39**, 1809–1827 (1989).
- [30] E.A. Kuznetsov and A.M. Rubenchik, "Soliton stabilization in plasmas and hydrodynamics," *Phys. Rep.* **142**, 103–165 (1986).
- [31] F.W. Dabby and J.R. Whinnery, "Thermal self-focusing of laser beams in lead glasses," *Appl. Phys. Lett.* **13**, 284–286 (1968).
- [32] C. Rotschild, M. Segev, Z. Xu, Y.V. Kartashov and L. Torner, "Two-dimensional multipole solitons in nonlocal nonlinear media," *Opt. Lett.* **31**, 3312–3314 (2006).
- [33] C. Rotschild, B. Alfassi, O. Cohen and M. Segev, "Long-range interactions between optical solitons," *Nature Phys.* **2**, 769–774 (2006).
- [34] M. Segev, B. Crosignani, A. Yariv and B. Fischer, "Spatial solitons in photorefractive media," *Phys. Rev. Lett.* **68**, 923–926 (1992).
- [35] C. Conti and G. Assanto, "Nonlinear Optics Applications: Bright Spatial Solitons," *Enc. of Modern Optics*, **5**, 43–55, R.D. Guenther, D.G. Steel and L. Bayvel eds., Elsevier, Oxford (2004).
- [36] A. Cheskidov, D.D. Holm, E. Olson and E.S. Titi, "On a Leray- α model of turbulence," *Proc. R. Soc. Lond. A* **461**, 629–649 (2005).
- [37] A. Ilyin, E.M. Lunasin and E.S. Titi, "A modified-Leray- α subgrid scale model of turbulence," *Nonlinearity* **19**, 879–897 (2006).
- [38] R. Penrose, "Quantum computation, entanglement and state reduction," *Phil. Trans. R. Soc. A*, **356**, 1927–1939 (1998).
- [39] P. Tod and I.M. Moroz, "An analytical approach to the Schrödinger-Newton equations," *Nonlinearity* **12**, 201–216 (1999).
- [40] W. Bao and Q. Du, "Computing the ground state solution of Bose-Einstein condensates by a normalized gradient flow," *SIAM J. Sci. Comput.*, **25**, 1674–1697, (2014).
- [41] G.J. Lord, D.P. Hof, B. Sandstede and A. Scheel, "Numerical computation of solitary waves in infinite cylindrical domains," *SIAM J. Numer. Anal.* **37**, 1420–1454 (2000).
- [42] J. Yang "Newton-conjugate-gradient methods for solitary wave computations," *J. Comp. Phys.* **228**, 7007–7024 (2009).
- [43] J.M.L. MacNeil, N.F. Smyth and G. Assanto, "Exact and approximate solutions for solitary waves in nematic liquid crystals," *Physica D* **284**, 1–15 (2014).
- [44] B. Fornberg and G.B. Whitham, "A numerical and theoretical study of certain nonlinear wave phenomena," *Phil. Trans. Roy. Soc. London A*, **289**, 373–403 (1978).
- [45] W.H. Press, S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, *Numerical Recipes in Fortran. The Art of Scientific Computing*, Cambridge University Press (1992).
- [46] M. Peccianti and G. Assanto, "Incoherent Spatial Solitary Waves in Nematic Liquid Crystals," *Opt. Lett.* **22**, 1791–1793 (2001).
- [47] A.A. Minzoni, L.W. Sciberras, N.F. Smyth and G. Assanto, "Steering of optical solitary waves by coplanar low power beams in reorientational media," *J. Nonlin. Opt. Phys. Mater.* **23**, 1450045 (2014).
- [48] A. Piccardi, A. Alberucci, N. Tabiryan and G. Assanto, "Dark nematicons," *Opt. Lett.* **36**, 1356–1358 (2011).
- [49] Y. Kivshar and G. Agrawal, *Optical Solitons: From Fibers to Photonic Crystals*, Academic Press, London (2003).
- [50] G. Assanto, T.R. Marchant, A.A. Minzoni and N.F. Smyth, "Reorientational versus Kerr dark and grey solitary waves using modulation theory," *Phys. Rev. E*, **84**, 066602 (2011).
- [51] A. Alberucci, M. Peccianti, G. Assanto, A. Dyadyusha and M. Kaczmarek, "Two-color vector solitons in nonlocal media," *Phys. Rev. Lett.*, **97**, 153903 (2006).
- [52] A.A. Minzoni, N.F. Smyth and A.L. Worthy, "Modulation solutions for nematicon propagation in non-local liquid crystals," *J. Opt. Soc. Amer. B*, **24**, 1549–1556 (2007).
- [53] C. Conti, M. Peccianti and G. Assanto, "Observation of optical spatial solitons in a highly nonlocal medium," *Phys. Rev. Lett.*, **92**, 113902 (2004).
- [54] G. Assanto, A.A. Minzoni, N.F. Smyth and A.L. Worthy, "Refraction of nonlinear beams by localised refractive index changes in nematic liquid crystals," *Phys. Rev. A*, **82**, 053843 (2010).
- [55] A. Alberucci, G. Assanto, A.A. Minzoni and N.F. Smyth, "Scattering of reorientational optical solitary waves at dielectric perturbations," *Phys. Rev. A*, **85**, 013804 (2012).

Gaetano Assanto obtained an M.Sc. degree with honours from the University of Palermo, Italy in 1981 and a Ph.D. in optics from the University of Arizona, Tucson, Arizona in 1987.

He was a research associate at the Optical Sciences Center at the University of Arizona from 1988 to 1990 and a senior research scientist with CREOL, University of Central Florida from 1990 to 1992. He is currently Professor of Optoelectronics with the University of Rome "Roma Tre" and head of NooEL, the Nonlinear Optics and Optoelectronics Lab. His interests include parametric effects for all-optical processing, spatial solitons in quadratic and soft media, Ge-on-Si detectors for the near infrared, nonlinear optics in liquid crystals.

Dr. Assanto is a Fellow of the IEEE (Photonics Society), a Fellow of OSA and topical editor of various journals, including Optics Letters, Nature Scientific Reports and IOP Journal of Optics.

Noel F. Smyth was born in Brisbane, Queensland, Australia in 1958. He received his B.Sc. (honours) in mathematics from the University of Queensland, Brisbane, Queensland in 1980 and his Ph.D. in applied mathematics from the California Institute of Technology, Pasadena, California in 1984.

Between 1984 and 1987 he was a post-doctoral fellow at the California Institute of Technology, the University of

Melbourne and the University of New South Wales. He was a lecturer in the Department of Mathematics and Applied Statistics at the University of Wollongong between 1987 and 1990. Since 1990 he has been in the School of Mathematics at the University of Edinburgh, first as a lecturer (1990–1999), senior lecturer (1999–2004), reader (2004–2009) and finally professor of nonlinear waves (2009–present). He is the author of 4 book chapters and 122 articles. His research interests are in the general area of linear and nonlinear waves and nonlinear optics, including solitons, water waves, bores and waves in oceanography and meteorology.

Professor Smyth is a member of the American Physical Society, the Optical Society of America, the Society for Industrial and Applied Mathematics and the Australian Mathematical Society. He is a Senior Member of the Optical Society of America.